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RESEARCH MEMORANDUM

COMPARISON OF TURBOJET-ENGINE ALTITUDE PERFORMANCE CHARACTERISTICS AND IGNITION LIMITS WITH MIL-F-5624A FUEL, GRADES JP-3 AND JP-4

By Willis M. Braithwaite and Paul E. Renas

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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COMPARISON OF TURBOJET-ENGINE ALTITUDE PERFORMANCE CHARACTERISTICS AND IGNITION LIMITS WITH MIL-F-5624A FUEL, GRADES JP-3 AND JP-4

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SUMMARY

The altitude performance and ignition limits of an axial-flow turbojet engine were evaluated in an altitude test chamber with MIL-F-5624A, grade JP-3 fuel (that specified for this engine) and a low-volatility grade JP-4 fuel. The investigation was conducted over a range of altitudes from 10,000 to 55,000 feet.

Use of the JP-4 fuel resulted in an increase in specific fuel consumption of 2 to 5 percent over that obtained with the JP-3 fuel. This increased specific fuel consumption resulted from a combination of reduced combustion efficiency and the lower heat of combustion of the JP-4 fuel. Altitude ignition limits were found to be essentially equal for the two fuels over a range of flight Mach number and fuel-supply temperature. Inspection of the combustors after 6 hours operation with JP-4 fuel revealed no noticeable carbon deposition.

INTRODUCTION

The need for a fuel having characteristics suitable for jet aircraft and that could be produced in large quantities led to the development of MIL-F-5624A, grade JP-3 fuel. It was found, however, that during rapid climbs to high altitudes rapid boiling of this fuel occurred, thus resulting in large losses of fuel, both as vapor and as entrained liquid (foaming). Such fuel losses seriously decreased the range or endurance of the aircraft.

These losses may be reduced by using a fuel of lower volatility. Previous investigations (references 1 and 2) indicated that a reduction in volatility of the JP-3 fuel from a Reid vapor pressure of about 6 pounds per square inch to 1 pound per square inch resulted in no loss in altitude performance with respect to thrust, fuel consumption, and altitude blow-out, but decreased altitude ignition limits. On the

basis of these and other data, a compromise fuel specification, MIL-F-5624A, grade JP-4, was issued which limits the Reid vapor pressure to 2 to 3 pounds per square inch. It was therefore desirable to compare the performance of this new specification fuel with MIL-F-5624A, grade JP-3 in a full-scale turbojet engine developed on JP-3 fuel.

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Such a comparison of the altitude performance characteristics and altitude ignition limits of a current axial-flow engine using JP-3 and JP-4 fuels was obtained in an investigation conducted in an altitude test chamber at the NACA Lewis laboratory. Engine performance data were obtained at simulated altitudes of 10,000, 40,000, and 55,000 feet at a simulated flight Mach number of 0.6 for both fuels. Altitude ignition limits for both fuels were obtained at flight Mach numbers of 0.4, 0.6, and 0.8 with fuel-supply temperatures between 45° and 80° F. At a flight Mach number of 0.6, altitude ignition limits were also obtained for fuel-supply temperatures of about -35° and 0° F.

APPARATUS

Engine

A modern axial-flow turbojet engine was used for this investigation. Liners designated as a smokeless type were installed in the combustors. The ignition system used had a 15,000-volt, 400-cycle output to the plugs in two diametrically opposite combustors.

Altitude Test Chamber

The engine was installed in an altitude test chamber 10 feet in diameter and 60 feet in length, as shown in figure 1. The front of the engine extended through the front bulkhead by means of a labyrinth seal. This bulkhead separated the inlet and exhaust sections of the chamber. The inlet section was connected to the laboratory combustion-air supply and the engine exhausted into a diffuser elbow that was connected to the laboratory exhaust system. A rear bulkhead was located near the exhaust nozzle of the engine to prevent recirculation of exhaust gas around the engine. The altitude-chamber fuel system included a cooler to provide a range of fuel-supply temperatures from about -40° to 80° F.

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Instrumentation

Radial survey rakes at several circumferential positions were installed at the inlet and outlet of each component of the engine to measure total temperature and total and static pressure. The air flow was computed from the temperatures and pressures measured at the engine inlet, and the jet thrust was computed from this air flow and static and total pressures measured at the exhaust-nozzle inlet. The fuel flow was measured directly by rotameters in the fuel-supply line and the engine speed, by remote indicating tachometers.

Fuels

The fuels used in this investigation were MIL-F-5624A, grades JP-3 and JP-4. The specification and an analysis for each of the fuels are presented in table I. The JP-3 fuel is the fuel presently specified for the engine used in this investigation. The JP-4 fuel is one of the lower quality fuels permitted under this specification in that its Reid vapor pressure was 2.1 pounds per square inch, and the aromatics content was essentially the maximum allowed. The final boiling point of the fuel (561° F) slightly exceeded the 550° F allowed by the specification. The high final boiling point is believed insignificant.

PROCEDURE

Performance data were obtained at altitudes of 10,000, 40,000, and 55,000 feet for a flight Mach number of 0.6. At each flight condition, the engine-inlet temperature and pressure were set at values corresponding to the stagnation pressures and temperatures in flight, based on NACA standard atmospheric conditions. The exhaust section of the chamber was maintained at the static pressure corresponding to the particular altitude being simulated. The engine speed was varied from rated speed or the maximum engine speed limited by a tail-pipe gas temperature of 1300° F to an engine speed where the tail-pipe temperature was as low as 300° to 500° F.

The ignition limits were obtained at flight Mach numbers of 0.4, 0.6, and 0.8 with the fuel-supply temperature between 45° and 80° F. At a flight Mach number of 0.6, ignition limits were also obtained with fuel-supply temperatures of about -35° and 0° F. Because fuel characteristics have only a secondary effect on propagation of flame from one combustor to another and on engine acceleration, only the ignition phase of an altitude start was investigated. For the ignition studies, the engine-fuel manifold was modified to supply fuel only to the two combustors containing spark plugs, which reduced the amount of fuel

that would accumulate in the engine during an ignition attempt. If the combustors containing the spark plugs ignited, propagation to all combustors was assumed possible.

The altitude ignition limit was determined by simulating a particular altitude and flight speed in the altitude chamber. When the engine rotor speed stabilized, the ignition circuit was energized and the throttle advanced. If ignition did not occur, the throttle was closed and slowly advanced once more. This process of repeatedly varying the fuel flow was continued until ignition occurred or a time limit of 45 seconds had elapsed. Upon completion of two successive starts, the altitude was increased 2500 feet and the procedure repeated. When an altitude was reached where ignition could not be obtained after several attempts of 45-second duration, the altitude was lowered to that at which ignition has previously occurred. If ignition was again obtained, this altitude was, by definition, the altitude ignition limit for the engine.

RESULTS AND DISCUSSION

The effects of different fuel types on turbojet-engine performance will be apparent on variables including fuel consumption, combustor-outlet-temperature profile, and engine stability characteristics. Inasmuch as the dissimilarity between the fuels is not great, the combustor-outlet-temperature-profile effect was not considered. The engine exhibited stable operation over the range of engine speeds for the flight conditions investigated. Consequently, fuel flow, combustion efficiency, and specific fuel consumption are the only performance variables discussed. The data obtained in this investigation are presented in table II.

Performance Variables

The combustion efficiencies obtained with the JP-3 and JP-4 fuels at a simulated flight Mach number of 0.6 and altitudes of 10,000, 40,000, and 55,000 feet are presented in figure 2. The combustion efficiency presented herein is defined as the ratio of the enthalpy rise across the combustor to the enthalpy available from complete combustion of the fuel (reference 3). The JP-3 fuel gave consistently higher efficiencies at all three altitudes than did the JP-4 fuel. At peak efficiencies, this difference did not exceed 2 percent; at off-peak conditions, the largest difference in combustion efficiency was about 4 percent.

The lower combustion efficiency with the JP-4 fuel would require a higher fuel flow with this fuel than with JP-3 fuel; in addition, the

lower heating value of the JP-4 fuel is less than that of the JP-3, requiring a still higher fuel flow. The observed fuel flow is shown in figure 3. At an altitude of 10,000 feet, the increase in corrected fuel flow of the JP-4 fuel over that of the JP-3 fuel was slightly less than the increase indicated for the higher altitudes. At a corrected engine speed of 7500 rpm (approximate speed for peak combustion efficiency) and altitudes of 40,000 and 55,000 feet, the corrected fuel flow was about 3 percent greater for the grade JP-4 fuel than for the JP-3 fuel.

2474 The increased fuel flow required when JP-4 fuel was used resulted in a correspondingly higher corrected net thrust specific fuel consumption, as shown in figure 4. The corrected net thrust specific fuel consumptions with JP-4 fuel were 2 to 5 percent higher than with the JP-3 fuel. These data indicate no significant trend with increasing altitude.

Altitude Ignition

The effects of flight Mach number and fuel temperature on altitude ignition limits for the two fuels are compared in figure 5. On the basis of previous investigations (for example, reference 2), the more volatile JP-3 fuel might be expected to allow ignition at slightly higher altitudes than the less volatile JP-4 fuel. Nevertheless, as shown in figure 5(a), the altitude ignition limits of the two fuels differed by less than the altitude increment of 2500 feet used in determining the ignition limits. The altitude ignition limits presented in figure 5(b) for a range of fuel-inlet temperatures at a flight Mach number of 0.6 were also essentially equal for the two fuels. A slight decrease in altitude ignition limit occurred for both fuels as the fuel-inlet temperature was reduced from approximately 60° to -35° F.

The increased aromatic content and decreased volatility of the JP-4 fuel would be expected to increase the carbon deposition. Examination of one of the combustor liners revealed no noticeable carbon formation after 6 hours operation with this fuel; however, most of this operation was at high-altitude conditions where carbon deposition is minimized.

CONCLUDING REMARKS

A comparison of the performance of MIL-F-5624A grade JP-3 and a low-volatility MIL-F-5624A grade JP-4 fuel in a turbojet engine indicated that the combustion efficiency with the JP-4 fuel was 2 to 4 percent lower than with the JP-3 fuel at each of the three altitudes

investigated, 10,000, 40,000, and 55,000 feet. As a result of this lower combustion efficiency with the JP-4 fuel, together with approximately a 1-percent lower heating value, the engine net thrust specific fuel consumption was 2 to 5 percent higher with this fuel than with the JP-3 fuel.

The altitude ignition limits were essentially equal for the two fuels over a range of flight Mach numbers from 0.4 to 0.8. Similarly, the altitude ignition limits of the two fuels were essentially equal over a range of fuel-inlet temperatures from approximately 60° to -35° F. 2474

After 6 hours operation with the JP-4 fuel, which had a relatively high aromatic content, examination of one combustor revealed no noticeable carbon formation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

REFERENCES

1. Wilsted, H. D., and Armstrong, J. C.: Comparison of Performance of AN-F-58 and AN-F-32 Fuels in J33-A-23 Turbojet Engine. NACA RM E8K24, 1949.

2. Wilsted, H. D., and Armstrong, J. C.: Effect of Fuel Volatility on Altitude Starting Limits of a Turbojet Engine. NACA RM E50G10, 1950.

3. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN 1086, 1946.

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TABLE I - SPECIFICATIONS AND ANALYSIS OF FUELS

	MIL-F-5624A JP-3		MIL-F-5624A JP-4	
	Specifications	Analysis	Specifications	Analysis
A.S.T.M. distillation, (°F)				
Initial boiling point	----	117	----	148
Percentage evaporated				
5	----	156	----	188
10	----	178	250 (max.)	218
20	----	205	----	255
30	----	226	----	288
40	----	246	----	319
50	----	267	----	349
60	----	292	----	378
70	----	322	----	409
80	----	363	----	441
90	400 (min.)	415	----	475
95	----	452	----	499
Final boiling point	600 (max.)	487	550 (max.)	561
Residue, (percent)	1.5 (max.)	1.0	1.5 (max.)	1.1
Loss, (percent)	1.5 (max.)	1.0	1.5 (max.)	1.0
Freezing point, °F	-76 (max.)	Below -76	-76 (max.)	Below -76
Aromatics, (percent by volume)				
A.S.T.M. D-875-46T	25.0 (max.)	10	25.0 (max.)	----
Silica gel		9		25
Bromine number	30.0 (max.)	0.5	30.0 (max.)	8.0
Reid vapor pressure, (lb/sq in.)	5 to 7	5.8	2 to 3	2.1
Hydrogen-carbon ratio	----	0.172	----	0.160
Heat of combustion, (Btu/lb)	18,400 (min.)	18,680	18,400 (min.)	18,500
Gravity, (°API)	45 to 63	57.6	40 to 58	46.9
Air-jet residue, (mg/100 ml)	----	1.0	----	11
Accelerated gum, (mg/100 ml)	20.0	5.0	20.0 (max.)	15
Sulfur, (percent by weight)	0.4 (max.)	0.1	0.4 (max.)	0.1
Aniline point, °F	----	122.0	----	114.1
Viscosity at 70° F, (centistokes)	----	1.0	----	1.1

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TABLE II - PERFORMANCE DATA OBTAINED WITH

Run	Altitude (ft)	Mach number	Engine speed (rpm)	Altitude static pressure $\left(\frac{lb}{sq\ ft}\right)$	Compressor inlet total pressure $\left(\frac{lb}{sq\ ft}\right)$	Compressor inlet total temperature (^{o}R)	Exhaust-nozzle inlet total pressure $\left(\frac{lb}{sq\ ft}\right)$	Exhaust-nozzle inlet total temperature (^{o}R)	Engine air flow $\left(\frac{lb}{sec}\right)$
Grade JP-3									
1	10,000	0.6016	7643	1458	1862	519	3399	1671	75.98
2		.5907	6829	1457	1845	520	2627	1343	64.33
3		.6119	6067	1447	1863	520	2115	1096	53.06
4		.5953	5563	1455	1849	522	1882	1029	43.48
5		.5967	4932	1462	1860	520	1725	957	35.66
6	40,000	0.6152	8000	387.4	500.1	417	1113	1749	24.06
7		.6253	7586	386.3	502.8	417	1062	1604	23.84
8		.5938	6827	395.7	502.3	418	913.2	1363	22.33
9		.6052	6072	389.4	498.7	416	699.2	1089	18.79
10		.6186	5562	385.4	498.9	417	574.7	957	15.92
11	55,000	0.7206	8023	179.6	253.8	426	592.4	1876	11.51
12		.6285	7531	189.2	246.9	428	525.2	1715	11.29
13		.6336	6848	186.5	244.4	424	458.2	1510	10.53
14		.6447	6421	187.3	247.7	422	402.9	1295	9.52
15		.6204	7201	188.0	243.7	420	493.8	1555	11.21
Grade JP-4									
16	10,000	0.5126	7389	1454	1859	521	3133	1554	72.72
17		.6038	7078	1457	1864	523	2828	1425	67.71
18		.5896	6453	1459	1846	526	2303	1202	57.40
19		.5844	6072	1472	1855	524	2114	1105	52.30
20		.5800	5569	1477	1855	525	1887	1026	43.39
21	40,000	0.6103	7998	387.8	498.7	414	1127	1766	23.89
22		.6212	7592	386.3	501.1	413	1069	1608	23.88
23		.6196	7064	386.2	500.3	414	971.2	1437	23.16
24		.6228	6457	387.1	502.8	416	811.5	1230	20.92
25		.6159	5562	387.8	500.9	418	583.9	961	15.81
26	55,000	0.6059	7587	189.4	242.7	422	525.8	1720	11.23
27		.6344	7062	187.3	245.6	422	479.1	1554	10.94
28		.6196	6827	187.8	243.3	413	449.8	1474	10.61
29		.6455	6072	185.3	245.2	425	337.6	1204	8.76
30		.6173	6450	187.9	243.0	421	389.5	1301	9.68

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MIL-F-5624A, GRADES JP-3 AND JP-4 FUELS.

Engine fuel flow $\left(\frac{lb}{hr}\right)$	Net thrust (lb)	Thrust specific fuel consumption $\left(\frac{lb}{(hr)(lb\ thrust)}\right)$	Corrected engine speed (rpm)	Corrected air flow $\left(\frac{lb}{sec}\right)$	Corrected fuel flow $\left(\frac{lb}{hr}\right)$	Corrected thrust specific fuel consumption $\left(\frac{lb}{(hr)(lb\ thrust)}\right)$	Combustion efficiency	Run
Grade JP-3								
4452	3311	1.345	7643	86.34	5059	1.345	0.979	1
2623	1824	1.437	6822	73.86	3005	1.436	.974	2
1481	787	1.882	6061	60.33	1680	1.880	.970	3
1071	365	2.935	5546	49.91	1222	2.926	.971	4
760	74	10.219	4927	40.61	864	10.209	.957	5
1698	1282	1.324	8925	91.27	8017	1.477	0.944	6
1465	1162	1.262	8463	89.94	6878	1.407	.953	7
1067	878	1.216	7608	84.41	5009	1.355	.958	8
630	473	1.333	6782	71.37	2986	1.489	.949	9
449	245	1.833	6205	60.52	2124	2.045	.898	10
954	651	1.466	8855	86.97	8782	1.618	0.857	11
798	576	1.384	8293	87.85	7530	1.524	.906	12
598	454	1.317	7576	82.41	5728	1.457	.936	13
451	324	1.391	7121	73.32	4272	1.542	.888	14
675	522	1.292	8005	87.54	6513	1.436	.924	15
Grade JP-4								
3868	2803	1.380	7374	82.94	4394	1.377	0.968	16
3108	2183	1.424	7050	77.17	3514	1.418	.971	17
1939	1181	1.643	6415	66.19	2210	1.633	.967	18
1517	782	1.938	6042	59.95	1721	1.928	.956	19
1101	352	3.133	5536	49.79	1249	3.114	.944	20
1774	1298	1.366	8955	90.52	8426	1.530	0.922	21
1525	1176	1.297	8510	89.96	7219	1.454	.935	22
1238	991	1.248	7910	87.50	5863	1.398	.945	23
869	683	1.272	7212	78.83	4085	1.421	.945	24
472	252	1.872	6198	59.94	2222	2.086	.861	25
826	585	1.412	8414	88.28	7986	1.565	0.891	26
669	495	1.350	7832	84.97	6390	1.497	.923	27
591	445	1.329	7653	82.31	5761	1.489	.939	28
367	234	1.568	6710	68.37	3500	1.732	.901	29
459	239	1.395	7161	75.95	4439	1.548	.902	30

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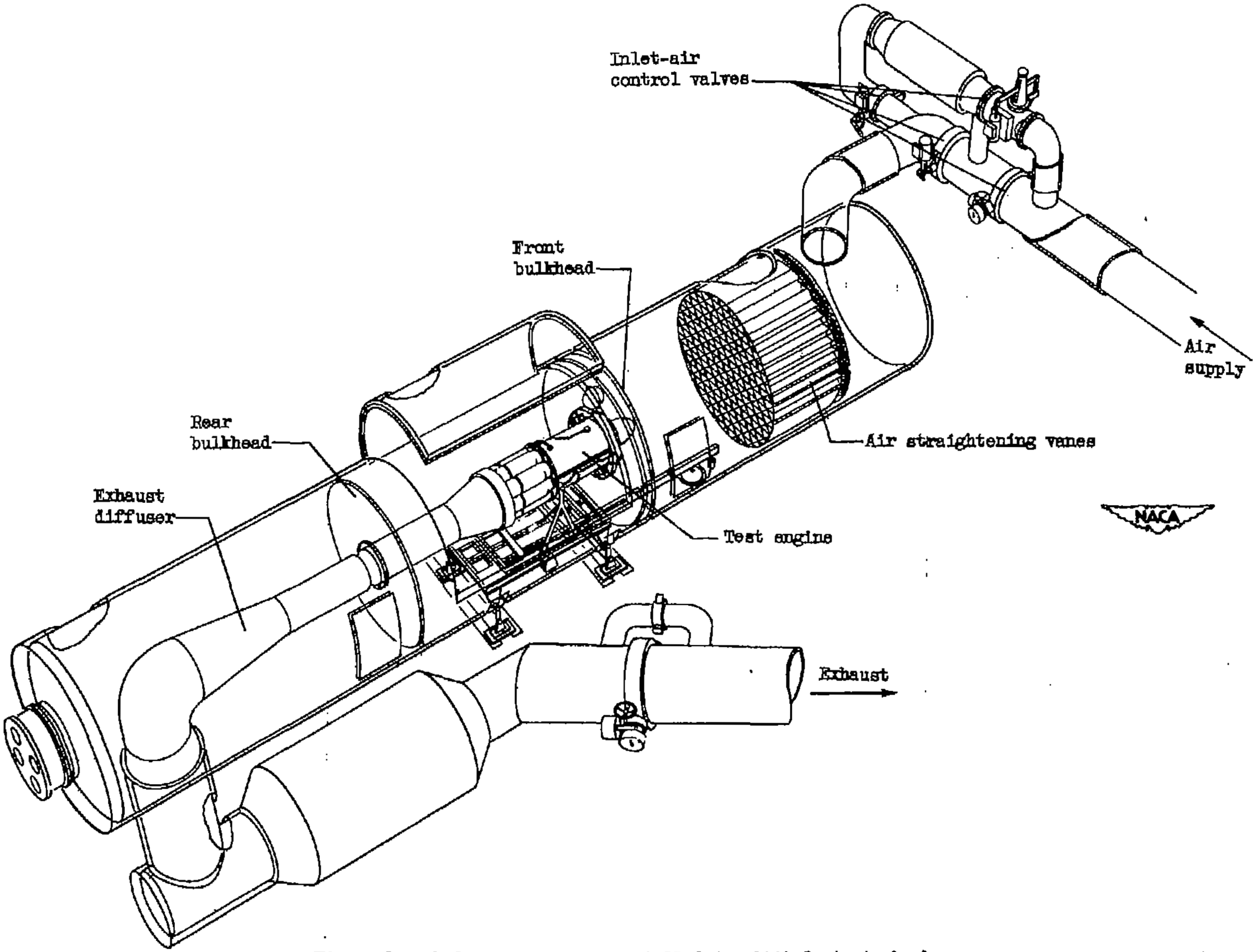

Figure 1. - Full-scale engine installed in altitude test chamber.

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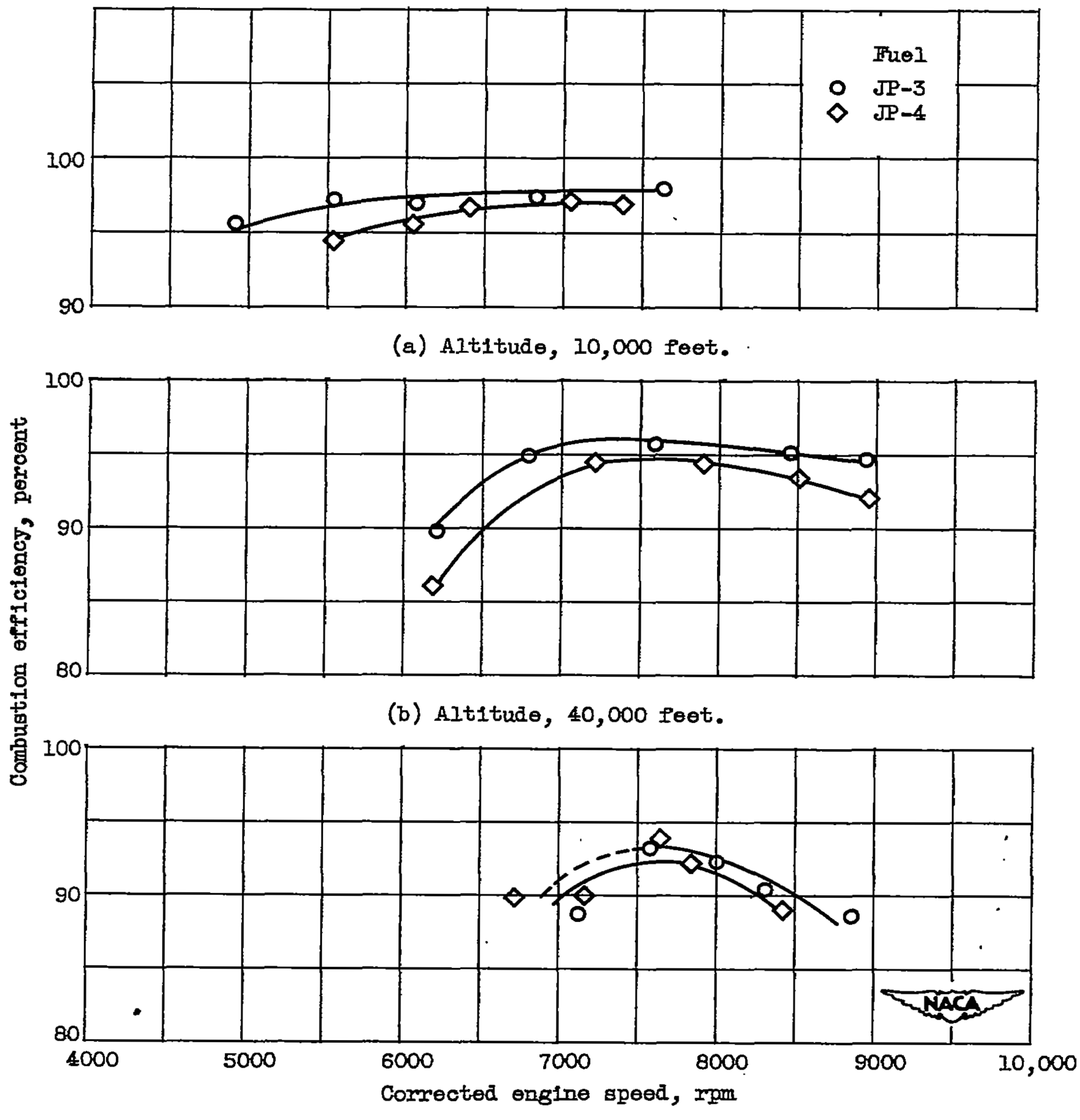


(c) Altitude, 55,000 feet.

Figure 2. - Comparison of combustion efficiencies for MIL-F-5624A, grades JP-3 and JP-4 fuels in full-scale engine. Flight Mach number, 0.6.

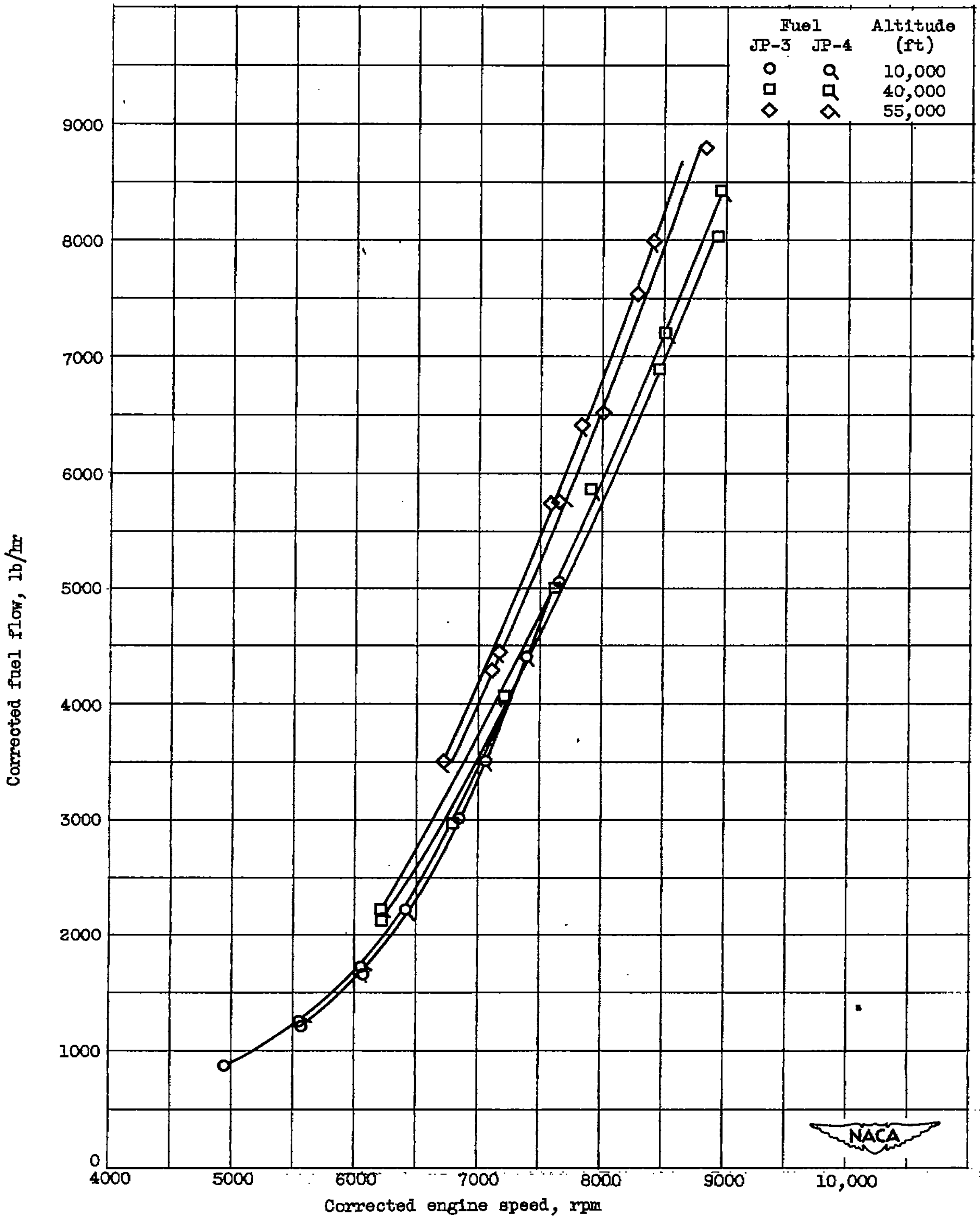
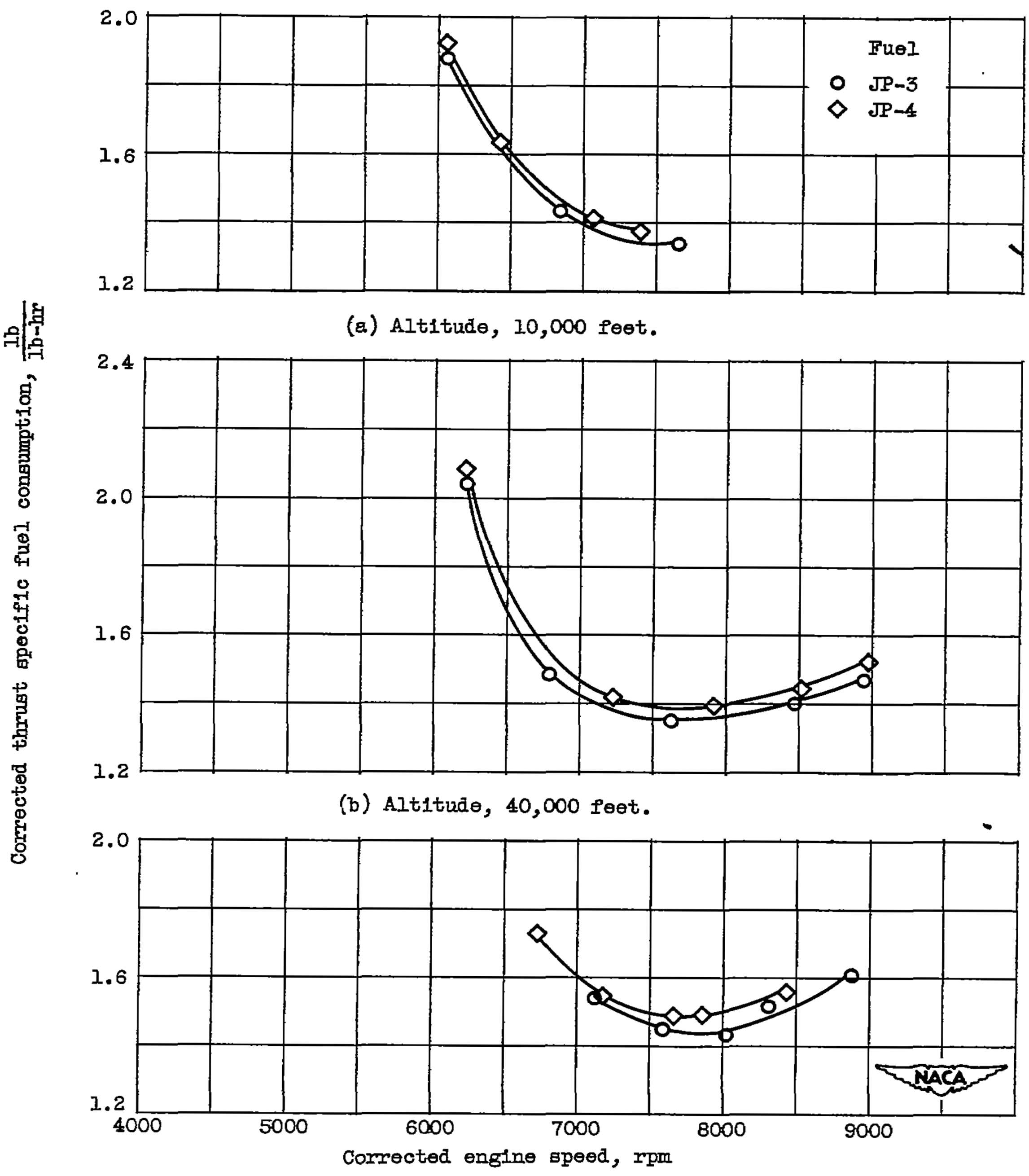


Figure 3. - Comparison of corrected fuel flows for MIL-F-5624A, grades JP-3 and and JP-4 fuels in full-scale engine. Flight Mach number, 0.6.

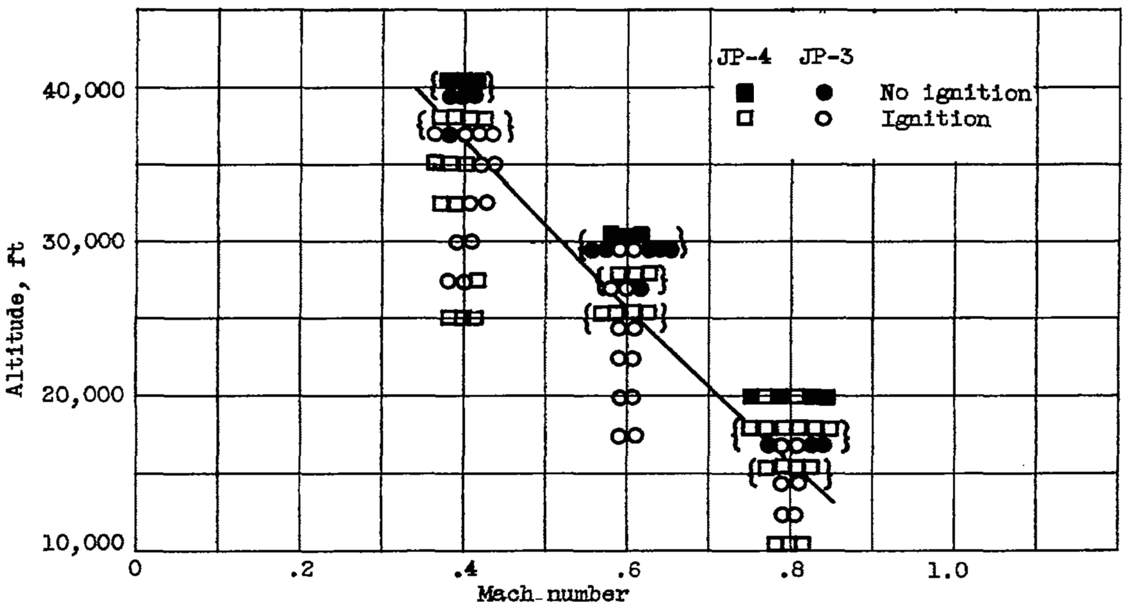


(a) Altitude, 10,000 feet.

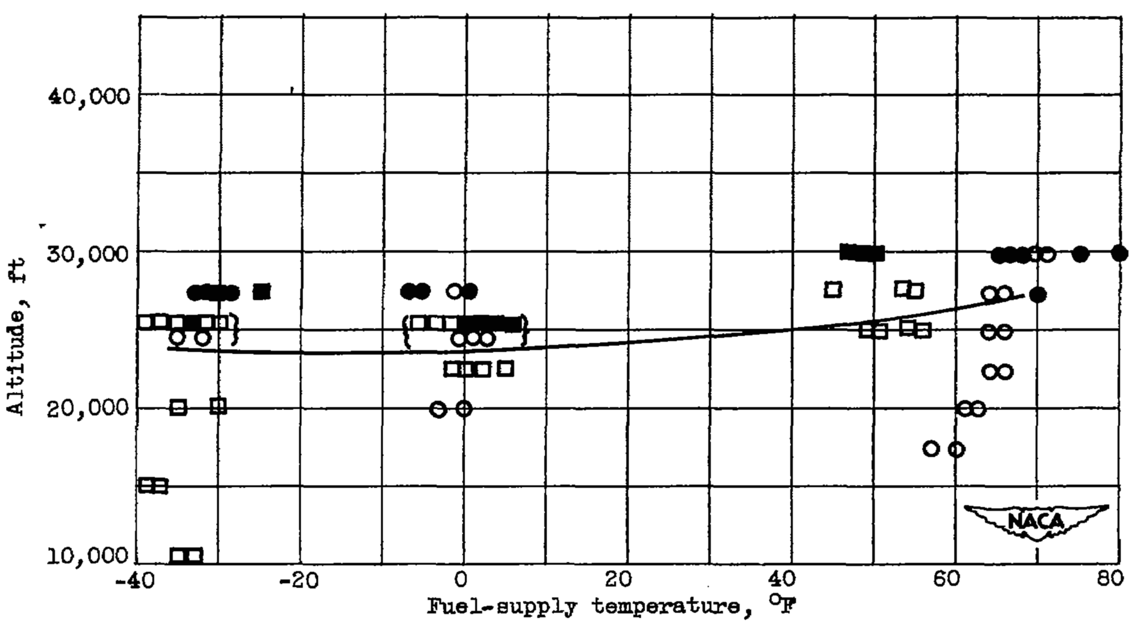
(b) Altitude, 40,000 feet.

(c) Altitude, 55,000 feet.

Figure 4. - Comparison of corrected net thrust specific fuel consumptions for MIL-F-5624A, grades JP-3 and JP-4 fuels in full-scale engine. Flight Mach number, 0.6.



(a) Effect of flight Mach number. Fuel-supply temperatures, 45° to 80° F.



(b) Effect of fuel-supply temperature. Flight Mach number, 0.6.

Figure 5. - Comparison of altitude ignition limits of full-scale engine obtained with MIL-F-5624A, grade JP-3 and JP-4 fuels as affected by flight Mach numbers and fuel-supply temperatures.

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